ARMY RESEARCH LABORATORY

Laser-Induced Breakdown Spectroscopy (LIBS) for Real-Time Detection of Halon Alternative Agents

by Cynthia K. Williamson, Robert G. Daniel,
Kevin L. McNesby, and Andrzej W. Miziolek

ARL-TR-2128   November 1999

19991129 019

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

Laser-Induced Breakdown Spectroscopy (LIBS) for Real-Time Detection of Halon Alternative Agents

Cynthia K. Williamson
NASA Langley Research Center, Atmospheric Sciences Division

Robert G. Daniel, Kevin L. McNesby, and Andrzej W. Miziolek
Weapons and Materials Research Directorate, ARL

Abstract

We report results of an evaluation of laser-induced breakdown spectroscopy (LIBS) for the detection of candidate halon replacement compounds (CF_4, CF_3H, CF_2H_2, and C_2F_5H). The fundamental (1.064 μm) from a Nd:YAG Q-switched pulsed laser was focused into an air flow containing 0.0005–5% of the analyte halocarbon compounds. The laser-produced plasma emission consists of a large number of intense fluorine atom lines in the 600–850-nm spectral range. Limit-of-detection studies indicate that LIBS can detect these compounds in the parts-per-million range. Also, we have recorded single-shot LIBS spectra with good signal-to-noise ratio (S/N) using an intensified photodiode array. Our results indicate that LIBS is a promising detection technique for in-situ and real-time measurement of halons during use in full-scale fire-suppression testing.

Acknowledgments

INTENTIONALLY LEFT BLANK.

Table of Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

List of Tables

INTENTIONALLY LEFT BLANK.

1. Introduction

Halons (halogenated hydrocarbons) are principally used for fire-extinguishing applications. Halons 1301 (CF_3Br) and 1211 (CF_2ClBr) are the primary compounds currently used by the military for fire suppression in various weapons systems. The eventual replacement of these compounds is of interest because of the ozone depletion potential (ODP) of bromine (Br) and chlorine (Cl)-containing compounds [1]. Virtually all of the halons released on the earth's surface eventually reach the stratosphere (ozone layer) through convection from the troposphere [2]. At high altitudes, the halons are photochemically degraded and the Br and Cl atoms become accessible for reaction with ozone and other atmospheric species [1, 2]. The production of new halons has been prohibited since 1 January 1994, in accordance with the Copenhagen Amendments to the Montreal Protocol on Substances that Deplete the Ozone Layer [3].

The candidate alternative compounds that are studied in this report are as follows (commercial names): C_2F_5H (FE25, HFC125), CF_4 (FE14), CF_3H (FE13, HFC23), and CF_2H_2 (FE12, HFC32). The detection of the alternative agents is of practical concern in order to monitor their concentrations during full-scale fire-suppression testing and to ascertain their effect on atmospheric chemistry. A routine method for real-time and in-situ detection of these compounds has not been previously reported. The development of a routine method has potential applications for field detection where identification, quantitation, and distribution are important parameters. Laser-induced breakdown spectroscopy (LIBS) is investigated here as a method for the detection of halon alternatives. The emission of fluorine (F), which is liberated in a plasma, is used for the analysis.

LIBS is a well-established technique based on the formation of a laser-induced plasma of the analyte [4]. A pulsed laser beam is focused to a fluence of approximately 10^8 to 10^9 W/cm^2 on or in the sample, which produces an avalanche of ionization or dielectric breakdown of the sample. The laser induces multiphoton ionization, which generates an initial electron density [5]. Continuum absorption of the laser radiation by the free electrons occurs, and electron collisions further ionize and heat the sample. The electron collisions directly generate the plasma by cascade ionization and

1

thus breakdown the sample. The emission of the atomic and molecular constituents that are excited within the plasma is then collected with lenses or fiber optics. Typical LIBS plasma temperatures are in the 20,000–25,000-K range for gases at atmospheric pressure [5].

The instrumentation required for the LIBS experiment is simple compared to other atomic techniques such as ICP and conventional electrode arc and spark spectroscopy. Complicated sample introduction equipment and electrodes are not necessary for the LIBS experiment. Also, LIBS has the capability of being used in situ, while ICP is not readily field deployable [6]. A standard sample chamber or probe can be implemented in LIBS; wavelength selection is accomplished by a monochromator or acousto-optic tunable filter and a photomultiplier tube (PMT), and photodiode array or CCD is used for signal detection. Time resolution of the LIBS signal is often performed due to the presence of a strong background plasma continuum emission (<2 ms) immediately following plasma generation. We have found the optimum delay for the detection of atomic analytes is from 1–2 μs out to 10–20 μs, depending on the analyte.

The majority of the LIBS studies have involved solid samples (e.g., paper, soils, paint, metals, steel); LIBS analysis of gaseous samples has been reported for the detection of F, Cl, sulfur (S), phosphorus (P), arsenic (As), and mercury (Hg) in air and column III V hydrides (e.g., B_2H_6, PH_3) [7–12]. The intent of the studies was the measurement of trace amounts of analytes in hostile environments and gas impurities for the hydride work. Hg was detected at the parts-per-billion level in air using a photodiode array detection system, which recorded single-shot spectra over a range of 20 nm [9]. Cremers and Radziemski [12] reported limits of detection of 8 and 38 ppm for Cl and F, respectively. SF_6 and chlorinated fluorocarbons (e.g., $C_2Cl_3F_3$) were the source compounds. The LIBS signal was time-resolved using a PMT/boxcar average for detection. A class of halon replacement compounds of particular interest is the hydrofluorocarbons (HFCs). C_2F_5H (FE-25) and CF_3H (FE-13) are candidates for military aircraft and ground combat vehicle engine compartment protection use.

2

The objective of the present study is the characterization of LIBS for the detection of halon alternatives. The ultimate goal is the application of this technique in a severely hostile fire-suppression testing environment. Spectra are recorded neat and in air since this is the most probable environment for samples collected in the field or analyzed in situ. The optimization of parameters unique to our system and an initial description of a practical field device for fire-extinguishing applications are described. Some methods for selective detection using LIBS are also considered.

2. Experimental Section

A schematic of the instrumental setup involving the photodiode-array-based detection system is shown in Figure 1. The Nd:YAG laser was operated at a repetition rate of 10 Hz and a wavelength of 1,064 nm. A photodiode illuminated by the laser radiation was the trigger source for the oscilloscope, boxcar (Stanford Research Systems [SRS], SR280) and pulser/photodiode array intensifier (Princeton Instruments PG-10/Princeton Instruments IRY1024G). The emission from the plasma was detected with a photomultiplier tube (EMI-Gencom Inc. 9658R) or gated photodiode array. Optical relay lenses were used to collect the emission for the PMT system and a single-strand fiber optic (Thorlabs, FP-600-UHT) was used in the photodiode array system. Data acquisition was computer-controlled with an SR465 interface for the PMT system. The laser energy was measured with an energy meter (Scientech Vector S200). The sample flow apparatus (Figure 2) was constructed from stainless steel tubing and swagelock connections and is similar to the configuration reported by Locke et al [13]. Argon (Ar) flowed through the outer tube, which functioned as a sheath and minimized the mixing of the analyte with room air. The inner tube contained the analyte/air flow. The sample flow apparatus was mounted on a three-dimensional stage in order to adjust the location of the analyte stream relative to the laser beam. The sample was mixed with air for limit of detection calculations. Gas flows were controlled by mass flow meters (MKS). Separate flows of air and the diluted analyte (900 ppm) were mixed before the sample flow apparatus. The total flow rate was varied between 100 standard cubic centimeters per minute (sccm) and 2 standard liters per minute (slm).
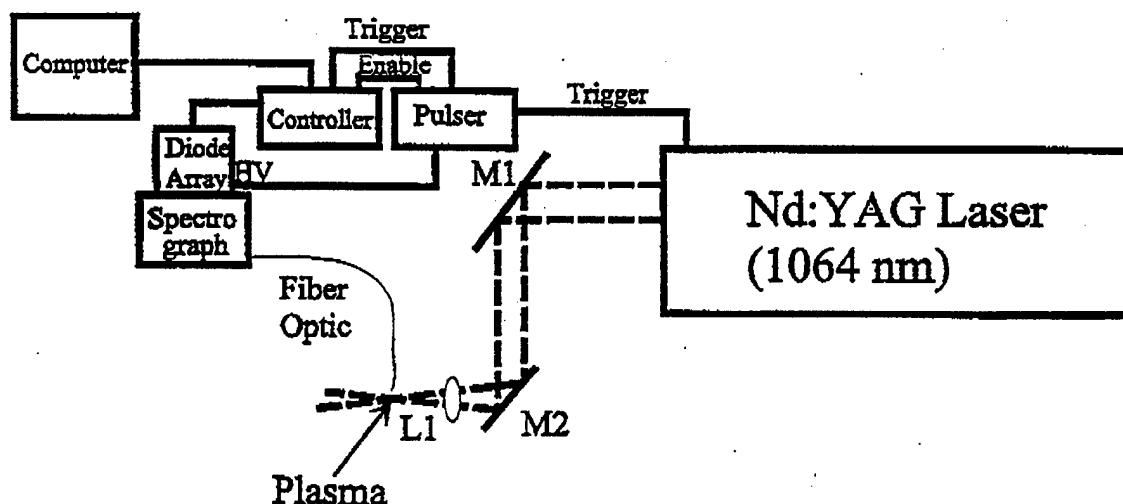
Trigger

Computer

Enable

Controller | Pulser   Trigger

Diode
Array HV

Spectro
graph   M1

Nd:YAG Laser
(1064 nm)

Fiber
Optic

L1   M2

Plasma

Figure 1. Schematic of Photodiode-Array-Based Detection System (M = Mirror, L = Lens).

3. Optimization

The optimal experimental conditions for the Ar sheath of the sample probe were determined by varying the Ar flow rate. Although the primary function of the Ar sheath is isolation of the plasma from the environment, an improvement of the S/N by a factor of 2 in the presence of the sheath was observed for samples mixed with air. The S/N ratio was calculated using the intensity of the LIBS signal at the emission maximum for F (685.6 nm). Table 1 lists the flow rates and the corresponding S/N for a 1% sample of CF_3H in air with a total sample flow rate of 2 slm. The optimal Ar flow rate was dependent on the sample flow rate and the position of the plasma. At Ar flow rates above 1 slm, the plasma was physically disrupted (i.e., changes in the shape, size, and position of the plasma within the boxcar averaging time). The increase in S/N with the Ar sheath may be due to stabilization of the plasma by isolation or repositioning. The laser beam was positioned approximately 1/8 in above the inner tube. The instability of the plasma increased at lower vertical positions, and dilution of the analyte may occur at substantially greater vertical positions.
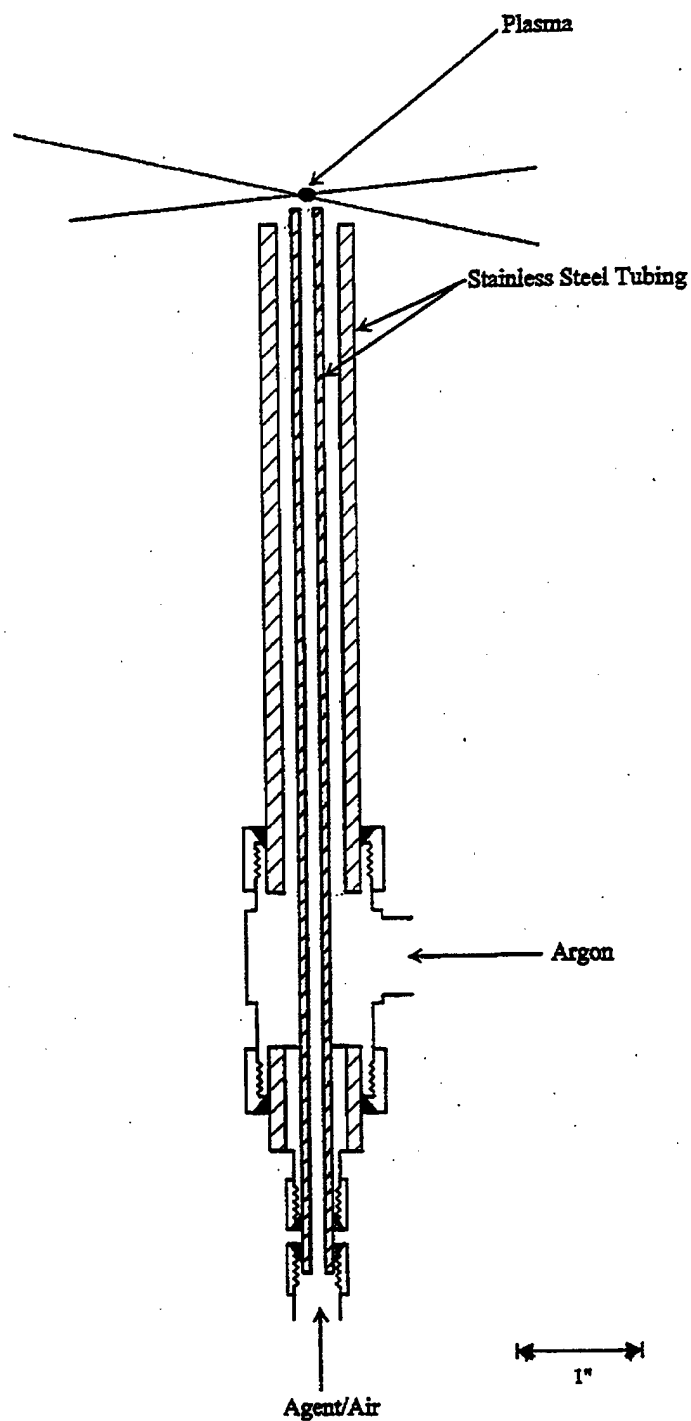
Plasma

Stainless Steel Tubing

Argon

1"

Agent/Air

Figure 2. Diagram of Sample Flow Apparatus Constructed From Stainless Steel Tubing and Swagelock Connections.

Table 1. S/N Dependence on Sheath Flow Rate

AR Sheath Flow Rate (slm)	S/N
1.5	90
1.0	62
0.5	102
0.3	68
0.0	50

A plot of S/N vs. laser energy (Figure 3) indicates that the optimal laser energy is approximately 120 mJ for our system (PMT/boxcar). The data were recorded with an Ar sheath flow rate of 500 sccm and a 1% mixture of CF_3H/air. The signal increased 240% at 200 mJ, compared to 60 mJ, but a substantial increase in the noise degraded the S/N at the higher energy. The laser amplifier was required to obtain energies above 120 mJ. An increase in the shot-to-shot variation of the laser power was observed when the laser amplifier was employed. The standard deviation of laser energy measurements increased by factors of 1.9, 1.8, and 2.4 at 300 mJ, compared to 120 mJ for three measurements of 500 laser shots. The precision of the standard deviation measurement also decreased at greater energies. The noise in the LIBS signal increased by a factor of 2.3 from 120 mJ to 300 mJ. Also, the plasma was physically disrupted, (i.e., changes occurred in the shape, position, and size of the plasma within the measurement time) at high energies ($\geq$140 mJ), which could be another source of noise in the measurement.

The single-strand fiber-optic studies mapped the plasma for signal intensity vs. horizontal and vertical position of the fiber optic. The acceptance angle of the fiber optic was 24° with a core diameter of 0.6 mm. The horizontal and vertical coverage of the fiber optic was approximately 1.3 mm. The stage was moved in increments of 1 mm. The laser beam was approximately centered over the inner tube, which contained the analyte flow. A plot of LIBS signal intensity vs. horizontal position is shown in Figure 4 for two vertical positions relative to the bottom edge of the plasma. The boundaries for the visible emission from the plasma are indicated with dotted lines. The
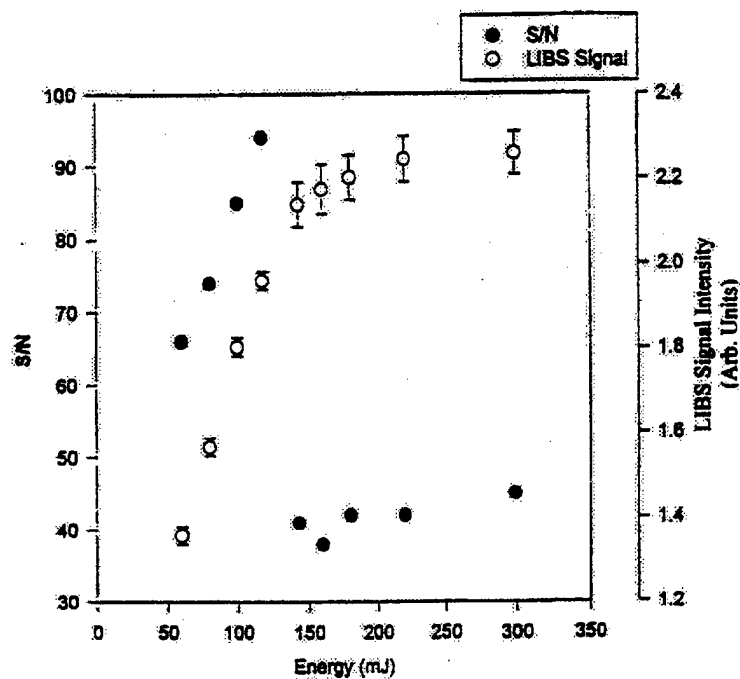
Figure 3. S/N and Signal Intensity of the F(I) Line at 685.6 nm vs. Laser Energy.
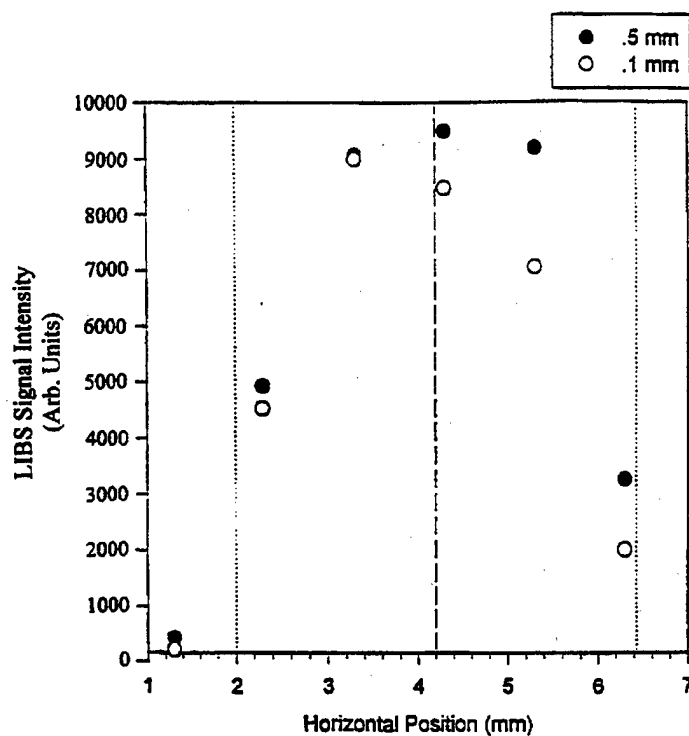

Figure 4. Signal Intensity at 685.6 nm at Different Horizontal Positions Plotted for 0.5 mm and 0.1 mm Over the Bottom Edge of the Plasma.

position of the limits of the plasma was estimated by locating the fiber-optic/millimeter stage in proximity to the plasma boundaries. The signal reached a maximum near the horizontal midsection of the plasma (dashed line). A contour plot of signal intensity at 685.6 nm for horizontal and vertical positions of the fiber optic is shown in Figure 5. The sample was 1% CF_3H in air. The diameter of the incident laser beam was approximately 6 mm, and the focal length of the lens was 90 mm. Thus, the diameter at the focus is approximately 0.02 mm (equation [1]).

$$w_2 \approx (f/w_1) \times (l/p)$$

$w_2 \equiv$ radius at focus

$f \equiv$ focal length of lens

$w_1 \equiv$ radius of laser beam   (1)

The beam focus should be in the vicinity of the highest contour. It is evident that a decrease in wavelength of the laser beam will produce a more confined beam focus. Decreasing the focal length of the lens should have the same effect. The dashed line indicates the approximate horizontal center of the plasma; the vertical center was not estimated. The LIBS signal intensity maximum contour is located from the center to the direction toward the laser. The plasma also expands in this direction with an increase in laser power, which has been noted by other researchers. The region of maximum intensity is approximately 1 mm in length, and, thus, the position of the fiber optic for optimal response is not critical.

4. Results and Discussion

The energy level diagram for the F atom transitions in the visible that are used for analysis is shown in Figure 6. Neutral atoms of F are detected with the LIBS technique used in this study. Atomic F is generated and excited in the plasma and relaxes by fluorescence. The relative intensities of the transitions, which were determined experimentally, from 683.4 to 690.9 nm are 3.3, 9.4, 3.0, 6.2, and 3.0 in order of increasing wavelength for a neat plasma of CF_4. The relative intensities were
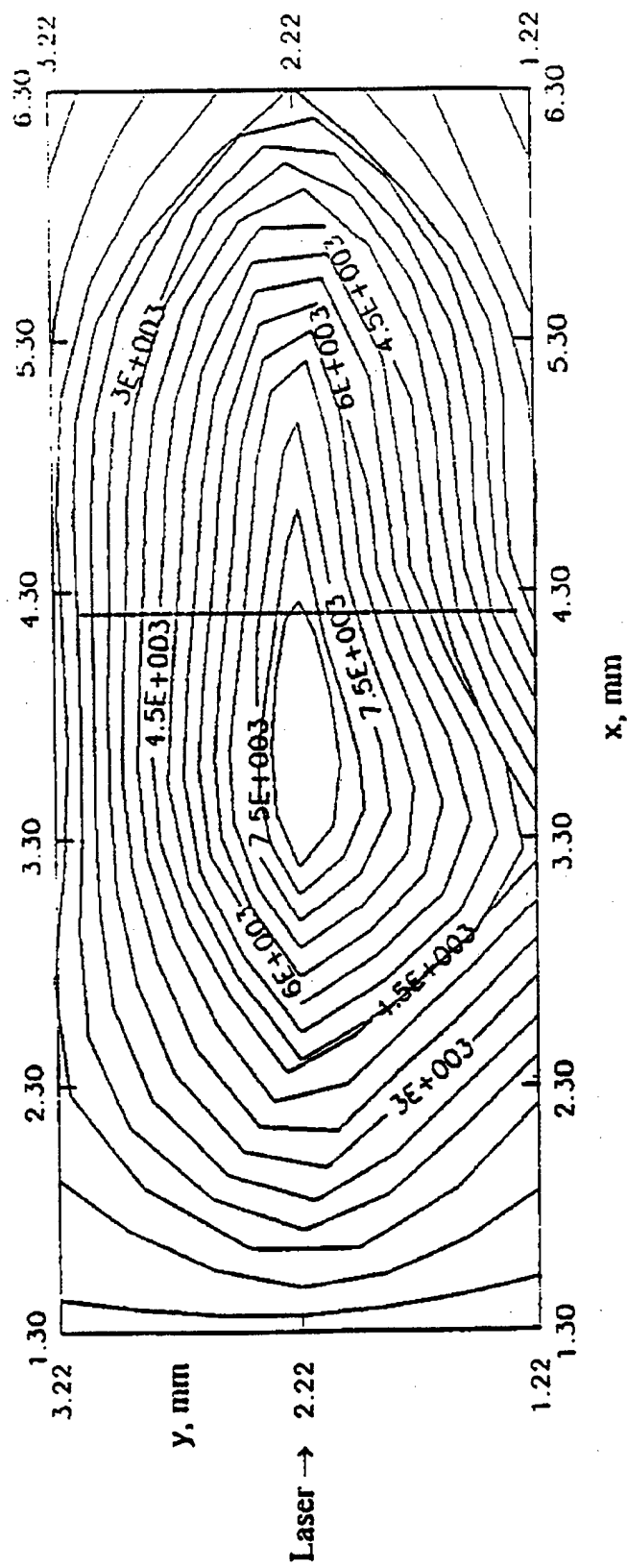
8

Figure 5. Countour Plot for Signal Intensity at 685.6 nm vs Different Horizontal and Vertical Positions in the Plasma.
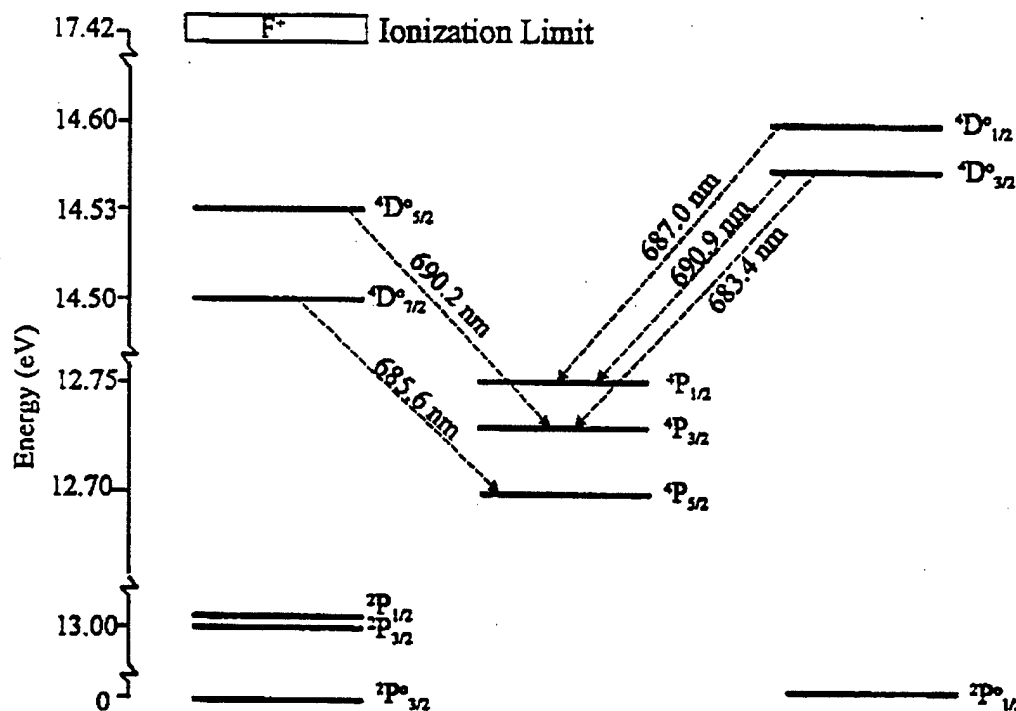
9

Figure 6. Partial Energy Level Diagram for F Atom With Transitions Used for Analysis Labeled.

comparable for the different agents. This indicates that the plasma temperature is similar for the different agents. Typical LIBS plasma temperatures are in the 20,000–25,000-K range for gases at atmospheric pressure [5]. Spectra of neat CF_4 collected with the PMT/boxcar system are shown in Figure 7. The boxcar gate width was set at 1 µs. The emission due to F(I) is clearly resolved with the maximum intensity at 685.6 nm. Emission from F(II) was not observed. Emission from the Ar sheath was observed at 810.4 nm, 811.4 nm, 840.8 nm, and 842.5 nm. The LIBS spectra of other agents were similar except that the intensity of the peak at 656.3 nm substantially increased due to hydrogen (H) emission, as shown in Figure 8 for neat CF_2H_2. This suggests a simple method to distinguish fluorocarbons and HFCs with LIBS and an alternative means to the F lines for detecting the HFCs. The greater linewidth of the H emission relative to the F lines is due to Stark broadening. The electron density, which indicates the degree of ionization, can be calculated using the H linewidth [5].

10
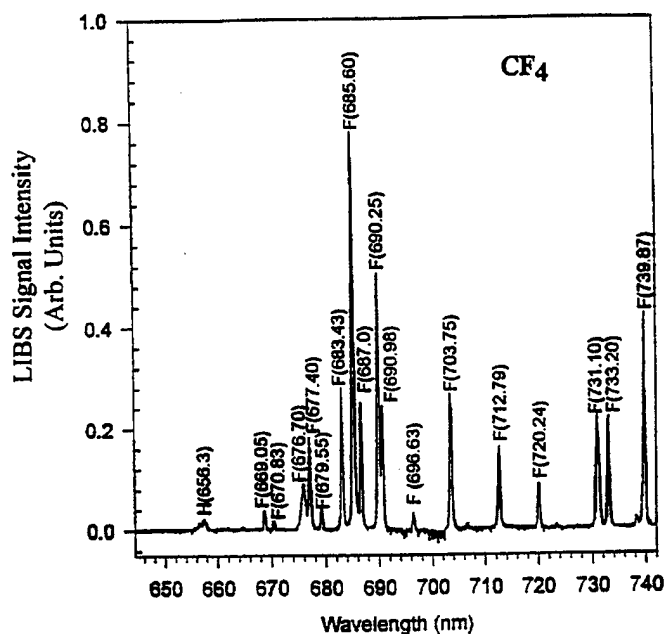
(a)
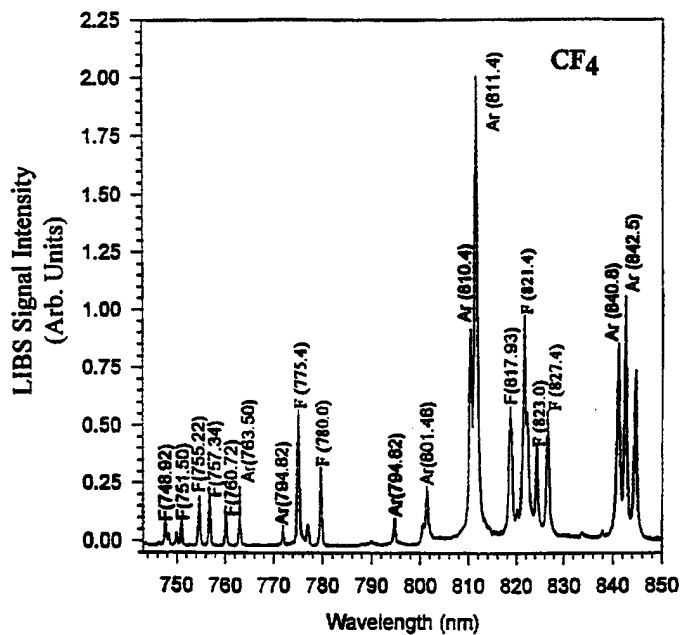
(b)

Figure 7. LIBS Spectrum in (a) Visible for Neat CF₄ Recorded With the PMT Detection System and (b) NIR for Neat CF₄ Recorded With the PMT Detection System.
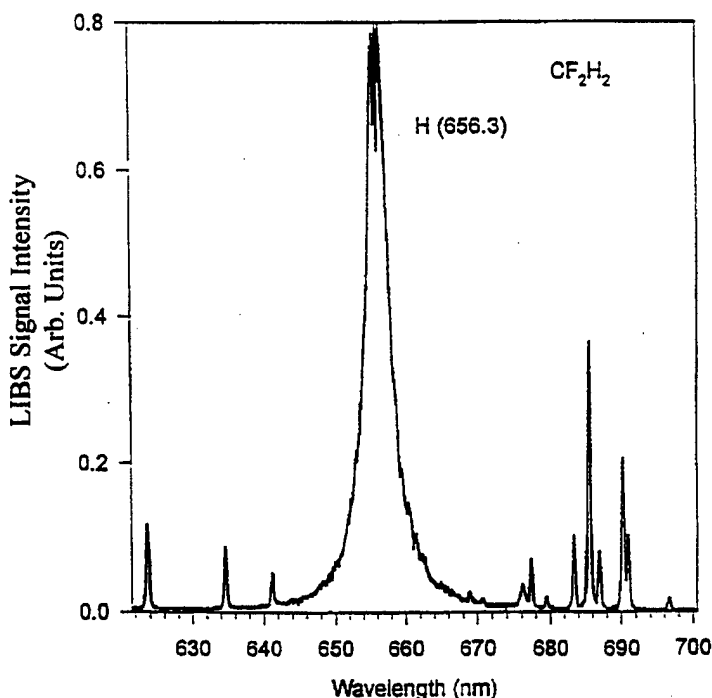
Figure 8. LIBS Spectrum of Neat CF_2H_2 Recorded With the PMT Detection System.

A spectrum recorded in air (Figure 9) shows emission from nitrogen (N) and oxygen (O). The main spectral region for F emission is free from interferences. The peak at 685.6 nm was used to determine a limit of detection (LOD) of 40 ppm for F in air using the PMT system. This LOD was calculated by multiplying the LOD obtained for CF_4 by four. This LOD was determined with a laser energy, of 120 mJ. This is compared to an LOD of 38 ppm with 190 mJ of laser energy, which was reported by Cremers and Radziemski [12]. The configuration implemented in this study does not use windows, which is an advantage for sensitivity, cost, and practicality. It was also observed by Cremers and Radziemski that the slope of the analytical curve is proportional to the number of F's in the compounds [12].

Single-shot spectra of 1% CF_3H in air recorded with the photodiode array/fiber-optic system are shown in Figure 10. The photodiode array system (Figure 1) was operated in a gating mode. The pulse width of the high-voltage gating pulse was set at 20 ms. The inherent RC time constant of the photodiode array was 5 ns. The optimal delay was not experimentally determined, but 1–2 ms was

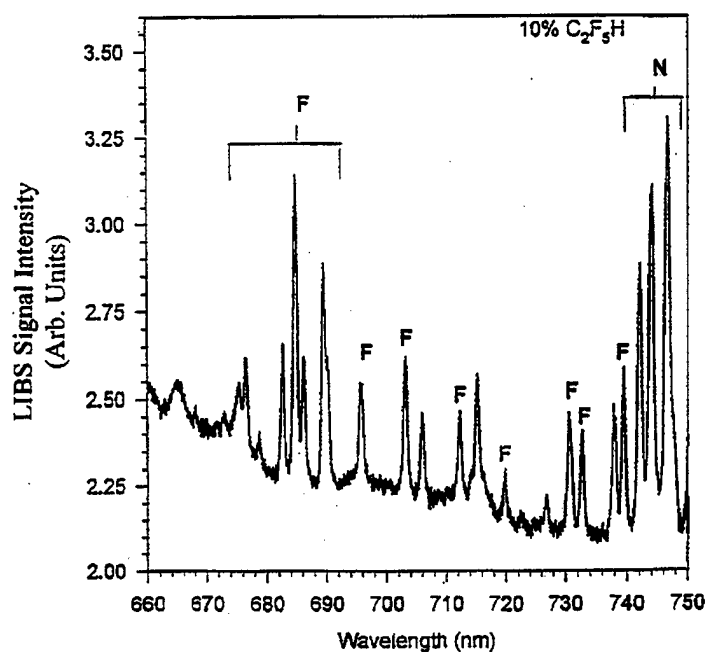12

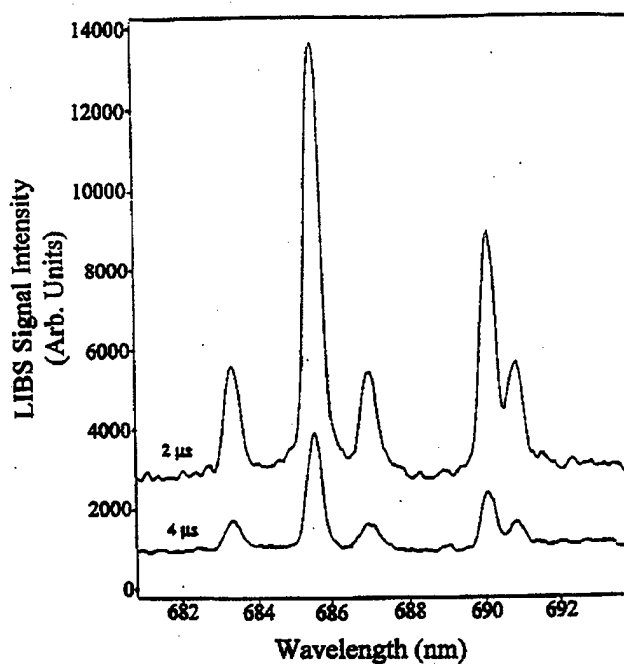**Figure 9. LIBS Spectrum of 10% C₂F₅H in Air Recorded With the PMT Detection System.**

Figure 10. Single-Shot LIBS Spectra of 1% CF₃H in Air at 2-ms and 4-ms Delay Times for the HV Pulse That Gates the Photodiode Array Intensifier.

13

routinely employed. This delay was reported in the literature for F [12]. The noise for five consecutive measurements of shot-to-shot spectra was 8%, and the LOD for F in air was 60 ppm.

The collection of one-shot spectra has significance for field measurements in fire-extinguishing applications. After release of the agent, its relative distribution can be determined with nanosecond time resolution. The initial distribution of the agent and its temporal evolution are important factors in predicting the efficiency of the agent for fire suppression and safety and determining how well the distribution system works. Multiple LIBS systems could be used to map the distribution of the agent in various locations of the test fixture. This can be accomplished inexpensively and practically with single-strand fiber optics and one charge-coupled device (CCD) (a two-dimensional array detector). Collection optics are not necessary for the detection fiber. Focusing optics are required to launch the excitation beam into the fiber. Applications that launch the excitation beam into a 1-mm fiber have been reported by other researchers [14]. Advanced optical techniques make it possible to deliver >50-mJ diffraction limited and multimode beams through large-core multimode fibers, with almost no degradation of beam quality [15]. Typical concentrations of the agents utilized in the field are 1–30%; thus, one shot spectra can be recorded without employing objectives for the detection fiber. As mentioned earlier, positioning the emission fiber is not critical. The detector can be remote since the fibers are inexpensive and inherently low-loss in the wavelength range of interest. The detection fiber can transmit to a portion of the CCD. Thus, the response of multiple LIBS detectors could be monitored simultaneously. For the fire-extinguishing application, the primary information needed is an indication of the amount of agent present in a given area at a specific time.

5. Conclusions

LIBS is a selective and sensitive technique for the detection of halon alternatives. The field utility of LIBS for fire-extinguishing applications appears feasible. Single-shot spectra can be recorded with nanosecond time precision for large-scale fire-suppression tests. Detection limits are

far below that required for field detection. In full-scale fire-suppression tests, it is conceivable that multiple excitation/collection fibers would be used to map the distribution of an agent.

INTENTIONALLY LEFT BLANK.

6. References

1. Wuebbles, D. J., P. S. Connell, and K. O. Patten. "Halon Replacements: Technology and Science." *ACS Symposium Series 611*, pp. 59–71, A. W. Miziolek and W. Tsang (editors), American Chemical Society, Washington, DC, 1995.

2. Solomon, S., R. R. Garcia, and A. R. Ravishankara. *Journal of Geophysical Research.* Vol. 99, pp. 20491–20499, 1994.

3. "Copenhagen Amendments to the Montreal Protocol on Substances that Deplete the Ozone Layer." Fourth Meeting of the Parties to the Montreal Protocol, 1994.

4. Radziemski, L. J., and D. A. Cremers. "Laser-Induced Plasmas and Applications." Marcel Dekker: NY, 1989.

5. Simeonsson, J. B., and A. W. Miziolek. *Applied Optics.* Vol. 32, pp. 939–947, 1993.

6. Yamamoto, K. Y., D. A. Cremers, M. J. Ferris, and L. E. Foster. *Applied Spectroscopy.* Vol. 50, pp. 222–233, 1996.

7. Cheng, E. A. P., R. D. Fraser, and J. G. Eden. *Applied Spectroscopy.* Vol. 45, pp. 949–952, 1991.

8. Casini, M., M. A. Harith, V. Palleschi, A. Salvetti, D. P. Singh, and M. Vaselli. *Laser and Particle Beams.* Vol. 9, pp. 633–639, 1991.

9. Lazzari, C., M. DeRosa, S. Rastelli, A. Ciucii, V. Palleshci, and A. Salvetti. *Laser and Particle Beams.* Vol. 12, pp. 525–530, 1994.

10. Hakkanen, H. J., and J. E. I. Korppi-Tommola. *Applied Spectroscopy.* Vol. 49, pp. 1721–1728, 1995.

11. Belliveau, J., L. Cadwell, K. Coleman, L. Huwel, and H. Griffin. *Applied Spectroscopy.* Vol. 39, pp. 727–729, 1985.

12. Cremers, D. A., and L. J. Radziemski. *Analytical Chemistry.* Vol. 55, pp. 1252–1256, 1983.

13. Locke, R. J., J. B. Morris, B. E. Forch, and A. W. Miziolek. *Applied Opics.* Vol. 29, pp. 4987–4992, 1990.

14. Marquardt, B. J., S. R. Goode, and S. M. Angel. *Analytical Chemistry.* Vol. 68, pp. 977–981, 1996.

15. Laverty, P. J. Private communication. CLEO Meeting, Baltimore, MD, May 1997.

INTENTIONALLY LEFT BLANK.

NO. OF		NO. OF	
COPIES	ORGANIZATION	COPIES	ORGANIZATION

2   DEFENSE TECHNICAL
    INFORMATION CENTER
    DTIC DDA
    8725 JOHN J KINGMAN RD
    STE 0944
    FT BELVOIR VA 22060-6218

1   HQDA
    DAMO FDQ
    D SCHMIDT
    400 ARMY PENTAGON
    WASHINGTON DC 20310-0460

1   OSD
    OUSD(A&T)/ODDDR&E(R)
    R J TREW
    THE PENTAGON
    WASHINGTON DC 20301-7100

1   DPTY CG FOR RDA
    US ARMY MATERIEL CMD
    AMCRDA
    5001 EISENHOWER AVE
    ALEXANDRIA VA 22333-0001

1   INST FOR ADVNCD TCHNLGY
    THE UNIV OF TEXAS AT AUSTIN
    PO BOX 202797
    AUSTIN TX 78720-2797

1   DARPA
    B KASPAR
    3701 N FAIRFAX DR
    ARLINGTON VA 22203-1714

1   NAVAL SURFACE WARFARE CTR
    CODE B07 J PENNELLA
    17320 DAHLGREN RD
    BLDG 1470 RM 1101
    DAHLGREN VA 22448-5100

1   US MILITARY ACADEMY
    MATH SCI CTR OF EXCELLENCE
    DEPT OF MATHEMATICAL SCI
    MADN MATH
    THAYER HALL
    WEST POINT NY 10996-1786

1   DIRECTOR
    US ARMY RESEARCH LAB
    AMSRL DD
    J J ROCCHIO
    2800 POWDER MILL RD
    ADELPHI MD 20783-1197

1   DIRECTOR
    US ARMY RESEARCH LAB
    AMSRL CS AS (RECORDS MGMT)
    2800 POWDER MILL RD
    ADELPHI MD 20783-1145

3   DIRECTOR
    US ARMY RESEARCH LAB
    AMSRL CI LL
    2800 POWDER MILL RD
    ADELPHI MD 20783-1145

ABERDEEN PROVING GROUND

4   DIR USARL
    AMSRL CI LP (BLDG 305)

INTENTIONALLY LEFT BLANK.

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1999	Final, January 1997 - May 1998

4. TITLE AND SUBTITLE

Laser-Induced Breakdown Spectroscopy (LIBS) for Real-Time Detection of Halon Alternative Agents

5. FUNDING NUMBERS

1L161102AH43

6. AUTHOR(S)

Cynthia K. Williamson,* Robert G. Daniel, Kevin L. McNesby, and Andrzej W. Miziolek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-BD
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-2128

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

* NASA Langley Research Center, Atmospheric Sciences Division, Mail Stop 401A, Hampton, VA 23681-0001.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We report results of an evaluation of laser-induced breakdown spectroscopy (LIBS) for the detection of candidate halon replacement compounds (CF_4, CF_3H, CF_2H_2, and C_2F_5H). The fundamental (1.064 µm) from a Nd:YAG Q-switched pulsed laser was focused into an air flow containing 0.0005–5% of the analyte halocarbon compounds. The laser-produced plasma emission consists of a large number of intense fluorine atom lines in the 600–850-nm spectral range. Limit-of-detection studies indicate that LIBS can detect these compounds in the parts-per-million range. Also, we have recorded single-shot LIBS spectra with good S/N using an intensified photodiode array. Our results indicate that LIBS is a promising detection technique for in-situ and real-time measurement of halons during use in full-scale fire-suppression testing.

14. SUBJECT TERMS

laser-induced breakdown spectroscopy (LIBS), halon detection, fire-suppression testing

15. NUMBER OF PAGES

24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author___ARL-TR-2128 (Williamson)___ Date of Report _October 1999_

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

_____

_____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

_____

_____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

_____

_____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

_____

_____

_____

CURRENT
ADDRESS

Organization

Name   E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD
ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)